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RESEARCH

A Critical Review of Measures for an Effective Application of Nano-Structured Coatings in Milling

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A B S T R A C T

The evolution of the coating deposition technologies led, among others, to the production of nano-structured coatings. Such coatings are often deposited on cutting tools since they contribute to an impressive enhancement of the coated tool life. Hereupon, attention has to be given for avoiding a rapid crack propagation due to a potential coating brittleness increase and for achieving a sufficient film adhesion. In this context, film residual stresses and structure may affect the film adhesion. This paper introduces characteristic measures for an effective application of nano-structured PVD and diamond coatings on cemented carbide tools in milling. More specifically, the adhesion of PVD HPPMS nano-structured coatings can be improved via an appropriate adhesive interlayer. Besides, the coating brittleness can be restricted through the application of nano multi-layer film structures. Furthermore, for improving the diamond coated tool performance, the diamond film nano-structure may be interrupted by micro diamond layers. The introduction of successive nano- and micro-structured layers restricts the film brittleness since micro-structured layers are more deformable compared to nano-structured ones. Finally, the interfacial fatigue strength of diamond coatings is affected by the film residual stresses. Inclined impact tests supported by appropriate FEM simulations facilitate the quantitative adhesion characterization of such films.

1. INTRODUCTION

Nano-structured coatings constitute the majority of the tools applied in material removal processes, among others, due to their elevated hardness [1,2]. However, only the application of nanostructured coatings cannot guarantee an improved wear behavior of the coated tools. More specifically, certain properties such as of the film adhesion to the substrate and the coating brittleness affect significantly the wear resistance of the coated tools. In the paper, characteristic measures to be undertaken for an effective application of nano-structured PVD and diamond coatings on cemented carbide tools in milling are presented. In this context, the usage of high power pulsed magnetron sputtering (HPPMS) as a PVD coating deposition technique is usually combined with the deposition of adhesive interlayers for exploiting the production of coatings characterized by enhanced mechanical properties and uniform film thickness [3-6]. The effectiveness of the adhesive nano-interlayers depends on the substrate surface's integrity and on the layer material [3,4]. Moreover, nano multi-layer PVD structures has to be applied for restricting the film brittleness [7,8]. Furthermore, diamond coatings deposited on cemented carbide tools are characterized by high residual stresses in their structure mainly due to epitaxial crystal differences and thermal expansion coefficients mismatch of the diamond coating and its cemented-carbide substrate [9-11]. Multi-layered diamond coating systems, with successive nano- and micro-structured layers, can absorb a part of the residual stresses because of the more deformable micro-structured layers compared to nanocomposite ones. The latter coatings possess increased brittleness due to their large compressive stresses which deteriorates the cutting performance [11]. It is worth mentioning that a prevailing mechanical property affecting significantly the cutting performance of diamond coated cemented carbide inserts is the fatigue strength of the diamond coating-substrate interface. The interfacial fatigue strength is temperature-dependent and is affected by the film residual stresses [12]. Inclined impact tests supported by appropriate FEM simulations facilitate the quantitative characterization of the films' adhesion [1,12].

2. PVD HPPMS COATINGS

2.1 Adhesive interlayers for improving the film adhesion

High Power Pulsed Magnetron Sputtering (HPPMS) process, compared to the standard dc sputtering techniques or cathodic arc, produces denser nanostructured coatings and free of droplets [3-6]. The goal of HPPMS technology is to achieve a plasma density exceeding conventional ones by roughly three orders of magnitude. Normal sputtering leads to a plasma density of 10^{16} m^{-3}, while HPPMS reaches 10^{19} m^{-3}. This is done by pulsing the power to the source with average amplitude of approximately 1 kW and peak power densities of about 0.4–0.5 MW per pulse, but at a low duty cycle of about 1–20 ms (see Fig. 1).

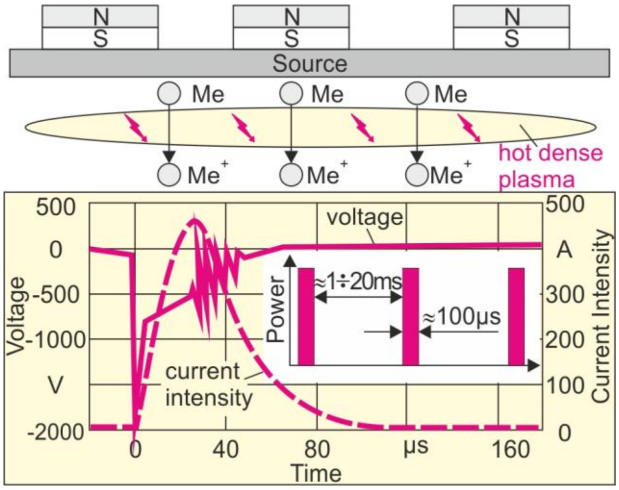


Fig. 1. Plasma energy increase by HPPMS during PVD processes.

In the developed hot and dense plasma area, the metallic atoms are highly ionized and subsequently deposited on the specimen surfaces with elevated kinetic energy.

The effectiveness of a coating deposited by HPPMS depends on the selection of an appropriate adhesive nano-interlayer, which immobilizes the WC carbides in reacting with high energy ions of the film material during their deposition on the substrate [4]. To evaluate the effect of different HPPMS deposited interlayers on the film adhesion, Rockwell HRC indentations and inclined impact tests were carried out on TiAlN coated inserts. No cracks or detachment signs appeared on the imprints of the coated insert with a Cr/CrN-nano-interlayer, indicating a good film adhesion (see Fig. 2a). However, inclined impact tests conducted on cemented carbide inserts with a Ti/TiN or W/WN nano-interlayer revealed the negative contribution of these materials on the adhesion. The related inclined impact test results are displayed in Fig. 2b. Moreover, milling investigations were carried out to examine the interlayer material effects on the coated tool wear behaviour (see Fig. 2c). The results revealed that HPPMS techniques jointly with a Cr/CrN nano-interlayer lead to significant cutting performance improvement due to adhesion enhancement.

The film adhesion and consequently the tool life improvements of HPPMS coated tools with a graded Cr/CrN nano-interlayer depend on the roughness of the employed cemented carbide substrates and on the adhesive interlayer thickness.

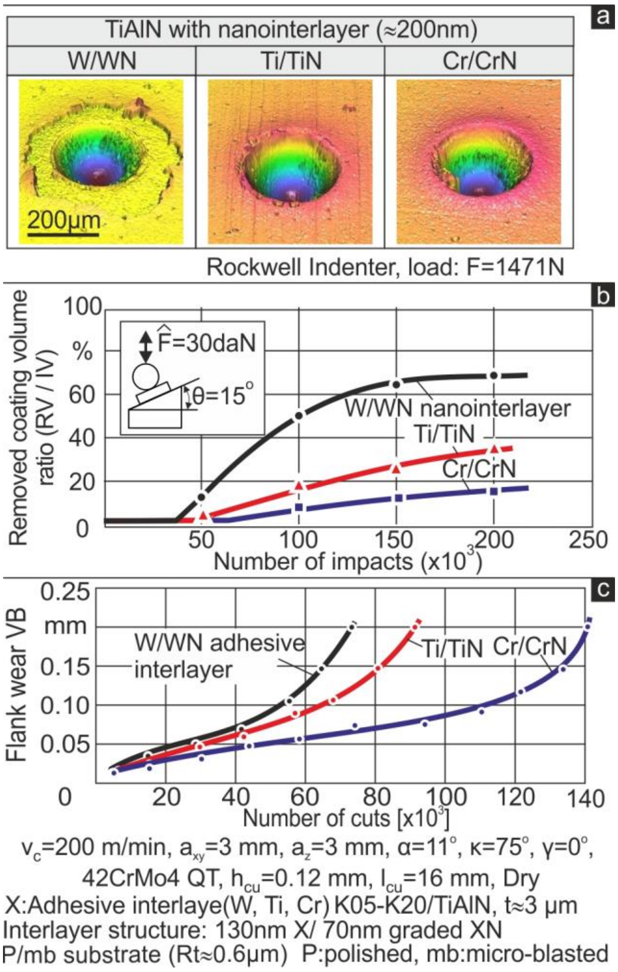


Fig. 2. Effect of HPPMS nano-interlayer's materials on the coating's adhesion characterized: (a) by Rockwell HRC indentations, (b) by inclined impact tests and (c) by cutting experiments.

By inclined impact tests, significant adhesion quality differences were detected when different HPPMS graded Cr/CrN interlayer thickness are employed [3]. The removed film volume ratios (RVR) versus the number of impacts on inserts with various interlayer thicknesses were registered during the inclined impact tests. The corresponding results are exhibited in Fig. 3a. The TiAlN coated inserts with graded Cr/CrN interlayers of 200 nm withstand more effectively the repetitive oblique impact loads compared to the corresponding interlayers of 50 and 600 nm thicknesses. Furthermore, the wear resistance of HPPMS TiAlN coated inserts with graded Cr/CrN-interlayer of various thicknesses was tested in dry milling (see Fig. 3b). According to the obtained results, the coated inserts with graded Cr/CrN nano-interlayer thickness of 200 nm exhibit the best wear resistance, reaching a tool life of approximately 140,000 cuts, at a flank wear VB of 0.2 mm.

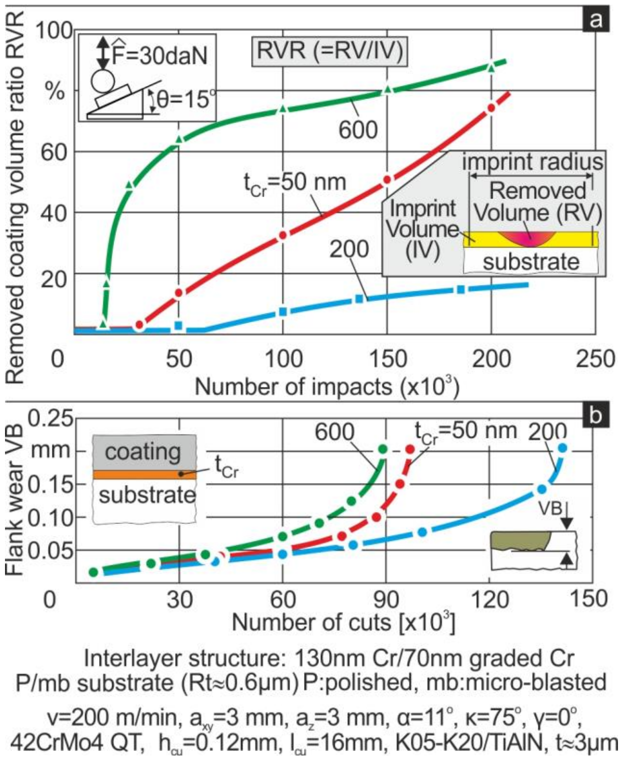


Fig. 3. a) Effect of interlayers' thickness on the removed film volume during the inclined impact test on HPPMS coated inserts (b) Flank wear development versus the number of cuts of HPPMS coated tools with different interlayer thickness.

Moreover, coated inserts with 50 nm and 600 nm nano-interlayer managed to cut only ca. 100,000 and 90,000 times respectively, up to the flank wear of 0.2 mm.

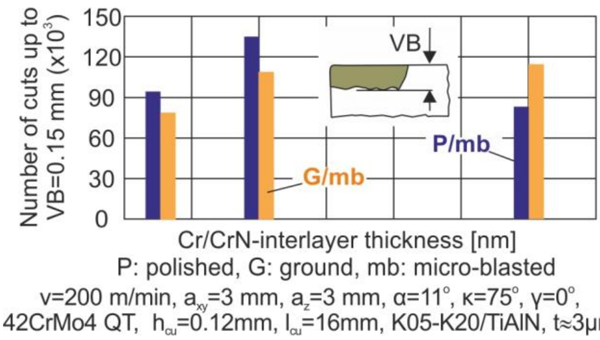
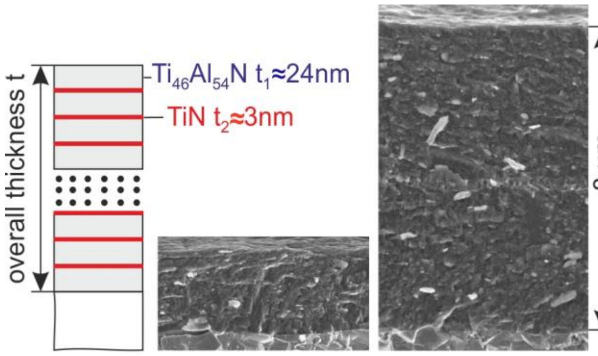


Fig. 4. Number of cuts up to a flank wear of 0.15 mm for various HPPMS interlayers thickness and substrate treatments.

Further milling investigations were conducted applying HPPMS TiAlN coated inserts with graded Cr/CrN-interlayer of various thicknesses and substrate mechanical treatments (see Fig. 4). In the polished and micro-blasted (P/mb) substrate treatment case, the coated inserts with nano-interlayer thickness of 200 nm exhibit the best performance.



thickness	2	4	8
Rt [μm]	≈ 1.1	1.3	1
Ra [μm]	≈0.11	0.14	0.13

SPGN 120308, $Ti_{46}Al_{54}N$/TiN coating,
substrate: HW-K05/K20, Deposition temp.=550°C,
3-fold substrate rotation

Fig. 5. The employed nano-layered coatings with various thicknesses and their roughness characteristics.

In the ground and micro-blasted substrates (G/mb), the tool life was increased, as the nano-interlayer thickness grows. The afore described differences are caused by the coatings' adhesion changes presented before.

2.2 Multilayer nano-structured PVD coatings for restricting film brittleness

The deposition of multilayer nano-structured PVD coatings on cemented carbide tools contributes to a significant improvement of the coated tool life due to their capability to prevent the crack propagation [7]. Characteristic SEM photos demonstrating cross sections of nano-layered HPPMS PVD TiAlN coatings with film thickness of approximately 2 µm and 8 µm are shown in Fig. 5. The coating structure consists of successive TiAlN and TiN layers. The thicknesses of the individual TiAlN and TiN layers amounted to roughly 24 nm and 3 nm correspondingly. In this way, the resulting structure of a coating with thickness approximately equal to 2 µm, 4 µm and 8 µm is the sum of around seventy-five, or one hundred fifty, or three hundred TiAlN layers alternately with an equal number of TiN ones respectively. Furthermore, the roughness characteristics of the used coated inserts are illustrated in Fig. 5. The roughness data are similar in all investigated coating thickness cases.

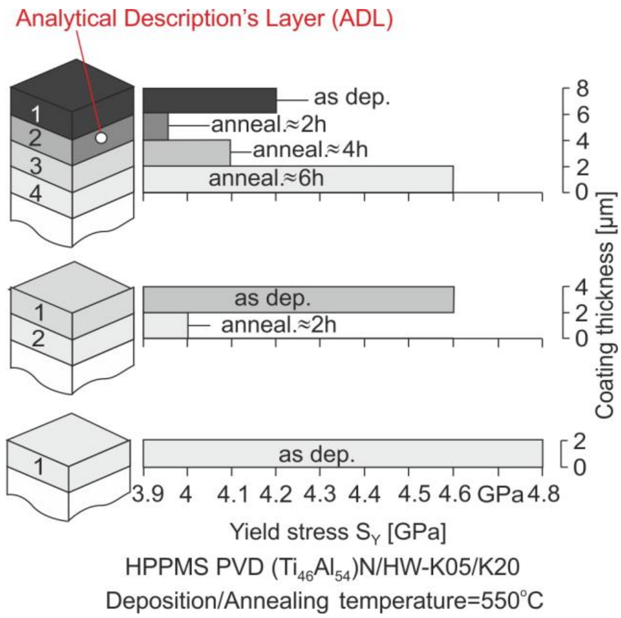


Fig. 6. Prediction of the graded strength properties of 8 µm, 4 µm and 2 µm thick nano-layered coatings.

The strength properties gradations versus the film thickness for the investigated nano-layered coatings are presented in Fig. 6. For estimating the graded strength properties of the used HPPMS PVD coatings, it was assumed that the structures of the 8 µm, 4 µm and 2 µm thick coatings are described by four, two or one individual layers (Analytical Description's Layers (ADLs)) respectively, each one possessing a thickness of 2 µm and own uniform properties. Every layer after its deposition at the HPPMS process temperature is exposed to an annealing affecting its strength data. The annealing duration of each layer is associated with the rest time, up to the deposition of the overall coating thickness. Coated inserts with film thickness of 2 µm, 4 µm and 8 µm were annealed in vacuum at a temperature of 550 °C equal to the related one during the film deposition. The annealing duration was adequately varied. To estimate the strength properties of the ADLs of the manufactured PVD films, nanoindentations coupled with appropriate FEM simulations were carried out on annealed coated specimens [7].

Coated inserts with diverse thicknesses were tested in milling. A characteristic metric for assessing the cutting performance of variously thick coatings is the VB evolution rate (R-rate) versus the cutting time. The R-rate is the ratio of the flank wear land width VB growth between two reference VB values divided by the overall removed chip length l_c between these values.

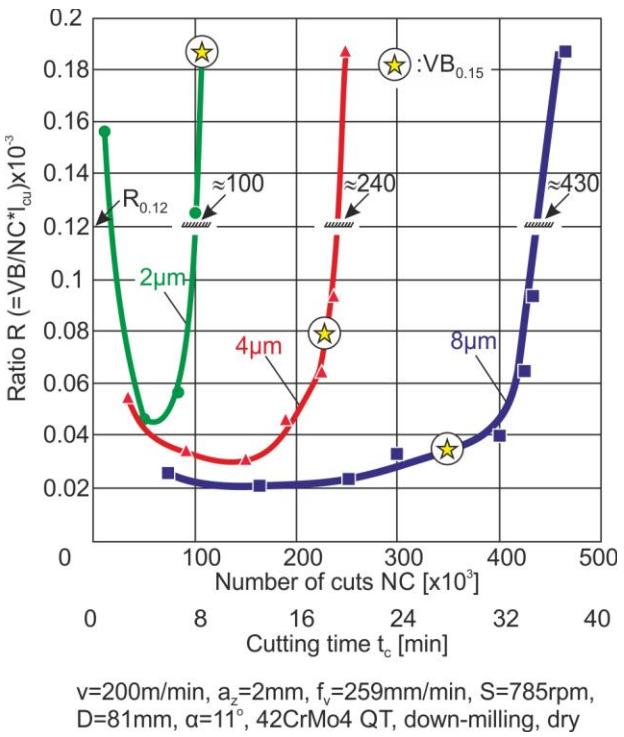


Fig. 7. VB-evolution rate development versus the number of cuts of coated cemented carbides inserts with different film thicknesses.

The latter parameter l_c is equal to the obtained number of cuts NC between the latter two VB values multiplied by the undeformed chip length l_{cu}. Figure 7 presents the R-ratio evolution versus the number of cuts NC and cutting time t_c in various film thickness cases. The R-rate was calculated at constant VB growth steps of 30 μm. The related numbers of cuts at the beginning and at the end of these steps were estimated by conducting milling experiments [7]. In the considered milling case, the undeformed chip length l_{cu} amounted to 16 mm. According to Fig. 7, the higher the coating thickness, the slower the R-rate evolution versus the number of cuts is. In the case of a 8 μm thick coating at a VB equal to about 150 μm, a low R-rate of roughly 0.04×10^{-3} [μm/mm] develops. On the contrary, in the case of a 2 μm thick coating, the R-rate at the same VB of 150 μm is roughly 4.5 times higher, equal to around 0.18×10^{-3} [μm/mm], thus rendering the tool change necessary. Hence, when using a 8 μm thick film instead of a 2 μm one, the obtained tool life was larger than 4 times at the same R-rate, as for instance at 0.12×10^{-3} ($R_{0.12}$ see Fig. 7). If the flank wear land width VB of 150 μm ($VB_{0.15}$) was used as criterion to compare the achieved tool lives when using a 2 μm and a 8 μm thick coating, the previously mentioned tool life increase would be approximately only 3.5 times larger (see Fig. 7). In this way, it can be stated that the usage of multilayer nano-structured films facilitates the effective application of thicker coatings in milling processes due to their restricted brittleness.

3. DIAMOND COATINGS

3.1 Multi-layered diamond coating systems for restricting film brittleness

Diamond coatings on hardmetal tools are characterized by high residual stresses. The residual stresses in diamond films are associated with numerous reasons such as epitaxial crystal differences as well as the significantly smaller thermal expansion coefficient of the diamond coating compared to its cemented carbide substrate [9,10]. The employed deposition parameters affect significantly the level of residual stress in diamond film structure.

For investigating the described dependencies, three groups of coated inserts were produced by varying the deposition parameters. The cooling time was held constant and equal to 9 h. Applying a deposition time of 10 h, the NCD insert group was manufactured. At this deposition duration, the structural residual stresses were negligible and mainly thermal ones were developed in the nano-composite film structure. Moreover, two further groups were created possessing nano-composite (NCD/hsrs), or multi-layer film structure (MLD) with overall ten successive and alternate nano- and micro-structured layers. These nano- and micro-structured layers had approximately 0.34 and 0.66 μm thickness, respectively. In the latter two coating cases, the deposition time was intentionally shortened. As a consequence, structural compressive residual stresses developed in the diamond coating structure, which were overlaid with the also compressive thermal ones.

For determining the maximum residual stress in the investigated diamond coatings, the experimental-analytical procedure described in [11,12] was employed. The experimental procedure comprises the conduct of inclined impact tests on the coated specimens. During this test, depending on the applied repetitive impact load, a fatigue failure in the NCD coating–

substrate interface develops after a certain number of impacts causing the film detachment.

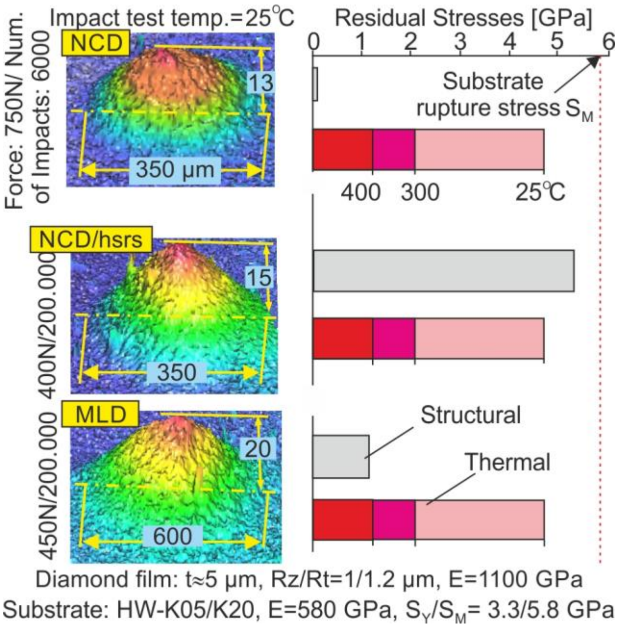


Fig. 8. FEM-calculated thermal and structural stresses in the investigated coatings based on the dimensions of the developed bulges at various loads and number of impacts.

After this damage, the highly compressive stresses in the NCD coating structure are released elevating the coating in the detached circular region up to a certain maximum height (bulge formation) [11]. Characteristic diamond film bulges developed at certain impact loads, after approximately the shown number of impacts are shown in Fig. 8. The bars at the right figure part demonstrate the determined thermal and structural equivalent stresses in the investigated coating cases. These stresses were determined by means of the mentioned analytical methods [11], taking into account the mechanical properties and the dimensions (diameter and height) of the formed bulges. In the case of NCD insert group, the structural residual stresses are negligible at ambient temperature compared to the thermal ones. On the contrary, the film residual stresses of NCD/hsrs and MLD coated inserts are attributed to both thermal and structural ones resulting during the CVD process and the subsequent cooling. The structural stresses in the MLD films are lower compared to the corresponding ones of the NCD/hsrs ones. Hereupon, it can be assumed that the micro-structured layers of the MLD coating absorb a part of the developed residual stresses, since they are more deformable compared to the nano-structured ones. The thermal residual stresses are reduced as the operational temperature grows, whereas the structural ones remain practically stable up to a temperature of roughly 400 °C.

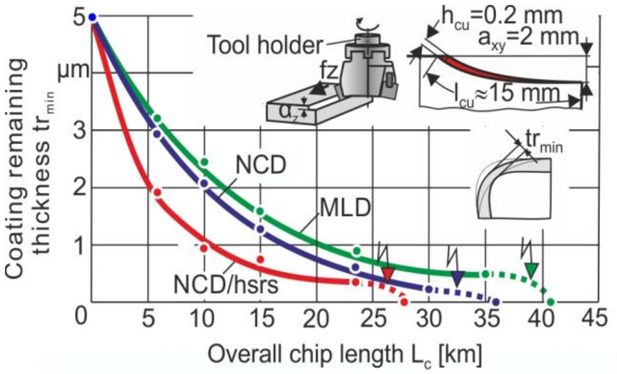


Fig. 9. Coating remaining thicknesses tr_{min} at various overall chip lengths L_c.

The cutting performance of the manufactured diamond coated tools was investigated in milling AA7075 T6. The experiments were performed without coolant or lubricant. For visualizing the coatings' wear evolution, the minimum coating thickness tr_{min} in the tool wedge roundness, at diverse overall chip lengths L_c, was determined with the aid of confocal microscopy measurements (see Fig. 9). The NCD/hsrs inserts demonstrated a worse cutting performance compared to the NCD and MLD ones. This can be attributed to the large compressive structural stresses in the NCD/hsrs films which may increase their brittleness and deteriorate the cutting performance. MLD coatings exhibited the best cutting performance reaching an overall chip length L_c of almost 40 km up to a substrate revelation at the cutting edge roundness region. Hereupon, the MLD coating withstand more effectively the repetitive impacts during milling, since the layer's interfaces obstruct the crack propagation and contributes to a tool life augmentation. Conversely, in the case of NCD films, the cracks usually propagate straight down to the substrate, worsening their wear behaviour in cutting.

3.2 Increased interfacial fatigue strength by controlling the developed residual stresses in the film structure

The cutting performance of diamond coated cemented carbide inserts is significantly affected by the film adhesion. Residual stresses in diamond films usually enhance the coating adhesion since they contribute to roughness locking in the coating–substrate interface. However, they may overstress the substrate material in its interface region, thus deteriorating the coating adhesion.

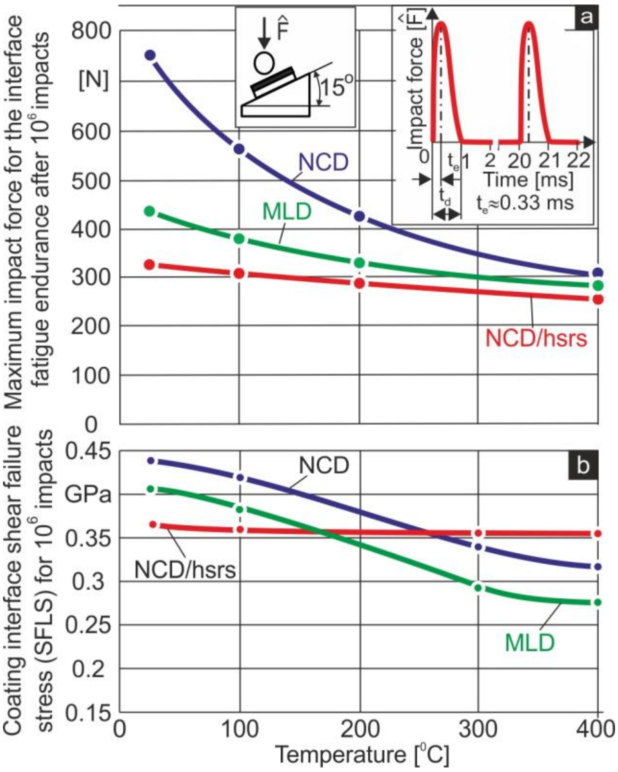


Fig. 10. (a) Interface fatigue endurance impact force. (b) FEM-calculated SFLSs associated with the interface fatigue endurance at various temperatures.

For determining the interfacial fatigue strength of the investigated coatings shown in Fig. 8, inclined impact tests were conducted. The experimentally detected maximum forces for avoiding the fatigue failure of the diamond coating–substrate interface after 10^6 impacts at diverse temperatures are illustrated in Fig. 10a. These critical impact forces and the temperature-dependent film residual stresses shown in Fig. 8 were the input data for calculating the shear failure stress (SFLS) according to the mentioned method described in [12]. The displayed SFLSs in Fig. 10b represent temperature-dependent thresholds triggering an interfacial coating–substrate adhesive failure in every coating case after 10^6 repetitive impacts. The higher the operational temperature, the lower the maximum applied force and the SFLS are for avoiding an adhesive film fatigue failure. At temperatures, less than approximately 200 °C, the lowest critical impact forces and SFLSs possess the NCD/hsrs coatings compared to the NCD and MLD ones. In this case, on the one hand, the sum of the structural and thermal residual stresses in the region of the film interface at temperatures less than approximately 400 °C is larger than the substrate rupture stress SM (see Fig. 8). Here, the temperature reduction to an ambient one leads to the formation of micro-cracks in the substrate interface region. In this way, the SFLS of NCD/hsrs films is lower compared to MLD and NCD coatings at temperatures less than about 100 °C. On the other hand, when the temperature grows, roughnesses between film and substrate in the interface region remain locked in the case of the NCD/hsrs films since the structural stresses are practically not affected. Hence, the related SFLS remains almost stable and over about 150 to 300°C it is greater compared to the related ones of the MLD and NCD films, respectively. In the latter two cases, the temperature increase causes an unlocking of interface roughnesses, thus deteriorating the film adhesion.

4. CONCLUSIONS

In this paper, characteristic measures for an effective application of nano-structured PVD and diamond coatings on cemented carbide tools in milling were introduced. The goals of these measures are to achieve a sufficient film adhesion to the substrate and to avoid a rapid crack propagation due to a potential coating brittleness increase. More specifically, in the case of HPPMS PVD coatings, the deposition of adhesive interlayers and application of multilayer nano-structured films for improving the film adhesion and decreasing their brittleness respectively, are recommended. Moreover, multi-layered diamond coating systems prevent the steep crack propagation in cutting processes. In the case of diamond coatings, special care has to be given to the residual stresses of the film structure. The latter affect significantly the film adhesion.

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